**"THE NEW MILLENNIUM PROGRAM: TECHNOLOGY DEVELOPMENT FOR THE 21ST CENTURY"**

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ABSTRACT

NASA's New Millennium Program (NMP), a space flight technology demonstration program that will validate the technologies needed to carry out the science missions that NASA envisions for the 21st century. The NMP is employing an innovative decision-making process to select the specific technologies that will be flight validated. First it has articulated NASA's vision of earth and space science exploration for the next century, then it has defined the capabilities needed to execute that vision, and finally it will select and demonstrate revolutionary technologies that provide those capabilities. This paper will discuss the investment needed to lay the technological groundwork for future low-cost, highly capable missions, the capabilities required for these missions, and the three-phase process that the NMP has devised through which high pay-off technologies are selected by the program for flight validation. It will show how a broad suite of revolutionary technologies, recommended in an initial phase by its Integrated Product Development Teams, will be narrowed down to a final optimal mix by subjecting them to a rigorous selection criterion, and eventually accepted and delivered for test flight. Through this process, the NMP will ensure that technologies chosen will truly enable its science-driven vision of space exploration in the new millennium.

INTRODUCTION

**Technology Investment:**
NASA has taken a bold and far-sighted step to seriously invest in revolutionary technology for the future with its New Millennium Program (NMP). In today's fiscal environment, where government funds are so constrained, and the political and public focus is on curbing government spending, it is difficult to convince the guardians of the treasury to invest in building a technological infrastructure for the country's space program that may not pay off until ten to fifteen years in the future. This situation is further complicated in that the societal benefits in terms of return on investment for a technology are extremely difficult to evaluate. In general, one can estimate the relative value of one technology by comparing it to another, particularly in a very closely related discipline. But comparing the value of, say, one computer technology to another is a much easier task than comparing it to the value of a welfare program, or a similar social investment.

The future well-being of the country lies both in the strength of its industrial and technological infrastructure and in the strength of its social programs, and there is a need to invest wisely in both. But the balance to be reached in deciding how much money to spend on each is always difficult. While both are to be considered as investments in the future, we are more aware of and affected by the shortcomings of the country's social programs in our everyday lives. The deficiencies in the country's technological infrastructure, however, are only apparent on an international level, when we have to compete with other countries in the global economic market.

The purpose of the New Millennium Program is to demonstrate and validate revolutionary technologies, in a series of flights that will be launched annually starting in 1998, to enable a new era in space flight. These technologies are expected to lay the groundwork and help build the technological infrastructure for NASA's space exploration and earth observation missions in the

21 st century. The vision articulated by NMP is one of frequent launches of space.mafl that are considerabl y more capable and less expensive than those of today.

In addition to the value of a new technology being hard to measure, the value of demonstrating a space technology tilt ough flight-validation is highl y debated issue as well. While it may be the most expensive way to test a technology to ensure that it works and is ready to be incorporated into science missions, it is also the most comprehensive and thorough means of testing the. technology's state of development and level of readiness. On the other hand, many features of the new technologies may be adequately demonstrated and tested on the ground, both functionally and environmentally, so the cost value of the space flight demonstration is often difficult to assess.

With other technology-validation programs, technologies are selected for flight-validation by evaluating the technology's state of development, and considering whether or not space flight validation is needed to further it along its development path. The decision for selection of a technology is often made without a clear understanding of that technology's relevance for mission application, and the process seems to be one of a solution looking for a problem. With the New Millennium Program, this situation is being avoided in the following manner: We have first articulated our vision for missions for the 21st century, then specified the capabilities needed to execute that vision, and finally are selecting technologies that will provide the capabilities and, in turn, enable our science vision. In this way, the technologies we select are a solution to the problem. In other words, they are problem driven technologies. So while the NMP is considered a technology program, it is in reality a science technology-needs-driven program. See Figure 1.

PROGRAM PROCESS

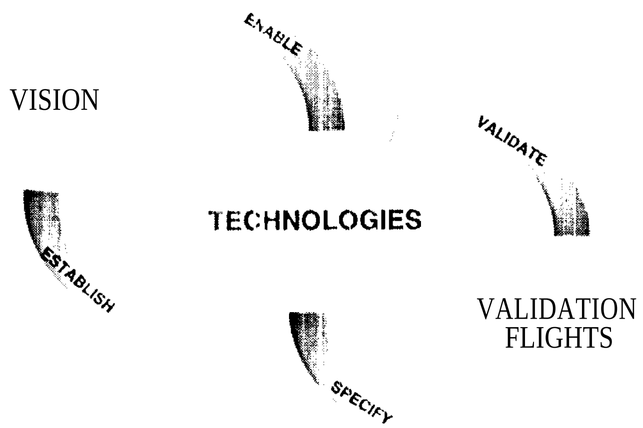


FIGURE 1

## Science Vision for the 21st Century

The science vision for the 21 st century, as articulated by the NMP, focuses on NASA's Earth and Space Science Program needs. In this context, these cardinal points are identified:

- A fleet of individual spacecraft to extend our range of targets
- Constellations to study dynamic systems and provide global coverage
- New measurement techniques to extend our scientific horizons

Our science vision includes sending networks of landers to Mars and Venus, clusters of probes mapping planetary ionospheres and magnetospheres, and spacecraft returning sample from asteroids and comets. Also, we see fleets of spacecraft exploring a diversity of targets such as

Pluto, the heliopause, and beyond. Constellations and networks of spacecraft will address dynamic and complex Systems. For example, a single lander can tell you about the Weather at one spot on a planet, but to characterize the dynamic climate of a planet, a network of landers is needed. Similarly, a single seismometer will indicate a planetquake, but a network of seismometers can use planetquakes to measure the size of a planetary core. We need multiple spacecraft to go beyond our initial reconnaissance to completely characterize dynamic systems the way we are able to on the surface of the Earth

An example of a high-priority mission to explore the universe is a free-ffying interferometer constellation capable of imaging extrasolar planets (see Figure 2---attached). Such a constellation could detect Earth-like planets and provide information that would clarify the origin and evolution of planetary systems in general.

Based on a widely spaced constellation of three or more spacecraft with precision formation control, this mission would require precision pointing and control of a constellation, nanometer-scale interspacecraft metrology, and accurate station keeping. Quiet spacecraft structures, low-thrust propulsion, and low-mass, high-quality optics are also needed capabilities to implement a free-flying, interferometer.

Comet-sample return missions also form a category of high-priority missions focused on our sol I" systems and grouped within the unifying theme of "Our Planetary Neighbors." Characterization of the primitive materials of which comets are composed will shed light on the origin and evolution of the solar system. The envisioned mission implementation includes the selection of an appropriate landing silt following at I orbital survey, in-situ study, selection and collection of local samples, and return of samples to Earth through a direct atmospheric entry.

To carry out such a mission, advances ill autonomous operations, low-mass structural materials and high, specific impulse propulsion will be required. High-capability, low-mass onboard computers and new approaches to sample handling and preservation are also needed capabilities.

**From the Vision to the Capability to the Technologies**

Increased capability, reduced cost, and increased flight rate will be achieved by using small launch vehicles that are enabled by microspacecraft and microinstruments. It will also be necessary to have shorter flight times and to decrease the size of missions operations staff through the use of intelligent flight systems.

<u>A Roadmap For Microspacecraft Development</u>: We could reduce spacecraft mass and reduce costs by miniaturizing spacecraft components. However, miniaturization alone would reduce our capabilities to obtain the science data required to fulfill our vision for the 21st century. Through the infusion of new technologies, such as innovative architectures and highly capable microdevices, we can develop new concepts that will actually increase our capabilities beyond what is currently possible, while simultaneously reducing our mission costs.

<u>Spacecraft Mass Decrease</u>: Because of the importance of bringing down spacecraft weight through the New Millennium Program, a chart illustrating how spacecraft mass has evolved over time was developed, showing the historical increase of spacecraft mass during the 1960s, 1970S and 1980S, and the start of decreasing spacecraft mass in the late 1980s and early 1990S (see Figure 3---attached). Projections for the future clearly show a rapid decrease in mass, made possible by a dramatic reduction in the size of digital electronics, and a concurrent increase in their capability.

<u>Capable Microspacecraft Flight Avionics</u> New chip technologies allowing three-dimensional stacking of microelectronics are examples of emerging technologies that can significantly reduce the mass and size of spacecraft subsystems. This new approach reduces multiple cards of electronics to single-chip stacks and can be applied to some of the massive spacecraft subsystems including onboard computing, power, and telecommunications systems. These novel stacking and interconnected technologies enable new integrated computing architectures and automated design methodologies, promising reduced design costs. In comparison to the Mars Pathfinder flight computer, this technology reduces the miss and volume by a factor of 100, with a 20-fold reduction in power, while enhancing the onboard capability.

Instrument Miniaturization: Small spacecraft require smaller instruments. Orders of magnitude reduction in instrument mass at 11. I \ 01 ı I me are anticipated through the infusion of new miniaturization technologies. A typical instrument deployed during the "flagship" era is the Microwave Limb Sounder carried by the Upper Atmosphere Research Satellite, launched in 1991 (see Figure 4---**attached**). At 250 kg, it towers over the human in the picture. in contrast, the Planetary Integrated Camera Spectrometer, incorporating multiplexed foreoptics, low-mass composite structures, and advanced focal plane technologies, has a mass of only **5 kg.**

Emerging microelectromechanical systems (MEMS) technology promises orders of magnitude reductions in the size of a variety of instruments for space exploration and Earth observation. Following in the footsteps of the microelectronics revolution, this technology extends on-chip capability beyond electronics to include mechanical and optical capabilities. MEMS technology enables new classes 01 microinstruments that make in-situ measurements a practical alternative to costly sample return for a variety of analytic measurements of planetary surfaces and atmospheres, as well as small-body investigations.

Future instruments incorporating MEMS, permitting on-chip integration of sensors and electronics, will reduce some instruments to mere grams in weight. A concept for a complete free-flying magnetometer with onboard power, data processing, and telecommunications, sees a mass of only a 1()() grams. The realization of such "spacecraft - on-a- chip" concepts will enable swarms of frc.c-flyers capable of mapping complex and (1\ namic systems in space.

Integrated microsensor packages are also small enough to be deployed as networks of microlanders and orbiters offering {1,1()1 ›al planetary coverage. For example, a network of microseismometers can provide information on global seismometry and could map the interior structure of planets. Similar] y, networks of micrometeorological sensors such as pressure sensors and hygrometers can be used to investigate planetary climate and complex atmospheric dynamics.

## Capabilities

**Once** having identified, in the broadest sense, the technologies needed to carry out 21st century space missions, it becomes necessary to group them into certain key areas and begin their focused development. To this end, Integrated Product Development Teams (IPDTs) have been formed within the NM]'. The integrated product (1 evelopment team concept is one that has been used highly successfully within private industry, and revolves around formation of a team with cross-departmental representation within a company. } or example, automotive companies have brought together members from their design, sales manufacturing, and strategic planning departments to work together making concurrent decisions to define and manufacture a final product.

'1'bough such cross-sectional representation has not traditionally been used to develop a product---design and sales departments, for instance, have widely differing views of what a customer wants and how much he's willing to pay -each department's individual input is vital for the success of the product in the marketplace, and IPDTs provide the mechanism for getting the best input and expertise simultaneously to influence how a product is developed. 'J hose companies that have usc(1 11'11'1's to manufacture low-cost, reliable, and thus highly desirable products find that their competitive. edge in the market is increased and they are able to operate very effectively.

One objective of the NM1' has been to improve the working relationships among government, industry, and academia in the development and application of technology; it is using the concept of IPDTs in a similar manner as private industry, but to bring together representatives from different Sect 01's of the country. Just as private industry uses 11'1)'1's to increase its competitive edge in its particular area of the market, this country can use NASA's NMP's IPDTs to increase its competitive edge in the area of global space exploration.

In implementing this concept, 11'11'1's for the Nh41' were formed around six key areas of technology:

1) Autonomy

2) Microelectronics
3) Telecommunic ations
4) Instrument Technolog ies and Architectures
4) in-Situ instruments and MicroElectroMechanical Systems (MEMS)
5) MAMS

These teams were then tasked to identify a broad suite of revolutionary technologies and select certain high-priority candidates in the initial phase of technology selection; to develop a roadmap for each of those technologies; to bring members from industry, government, and academia together within the teams; to spawn further partnerships with industry; and finally to deliver the technologies for flight validation.

The IPDTS were formed in August/September 1995 and have been working with great success ever since. Initial, startup issues such as membership, frequency of meetings, and so on were worked out by the teams themselves with little direction from the Program Office. The teams are self-govcrnillg and have proved highly effective in carrying out their charge. Each IPDT has a representative within each of NMP's mission Flight Teams for those technologies which are selected to be validated on a given flight. This arrangement is shown schematically in Figure 5--- **attached)**

Unlike IPDTs in private industry, where there is no contact among different teams, a working rule of the NMP IPDTs is that there be interaction among the teams. Though the 1} '1)3's in NMP focus primarily on their own scope of technologies they also interact with each other where their technologies are interdepen dent. For example, the software concepts which are developed by the autonomy team must be implemented and executed on the hardware which comes from the microelectronics team, Cross-fertilization among teams is facilitated through workshops and roadmapping.

At the program level, there are two annual workshops. The NMP Annual Technology Workshop is conducted each spring for all interested members of the government, industry, and academia. At the workshop, the overall program plan is discussed, as arc the validation flights, flight results, and plans for the future direction of the program Each 1} '1)'1' presents the latest version of its roadmap, and its fright plans and flight results to date. This workshop has a large attendance, with participants from the NMP program office, the 1} '1)-1's, industry, government, and academia. The 11'1)'1' Forum is the other annual workshop, and is conducted in the autumn. Participation in this workshop is limited to IPDT members only and some program office personnel. At this workshop the emphasis is on the IPDTs' roadmaps, and on cross-fertilization of ideas among the IPDTs.

## Technology Selection

After the initial phase of technology analysis- where **a suite** of breakthrough technologies will be incorporated within the roadmaps of the IPDTS the specific recommended technologies will be subjected to a more rigorous selection process Four individual evaluations **take place in the process of** identifying technologies for development for validation flights, as described in the following.

1. <u>Assessment of Technology Value</u>

Once the IPDTs have identified a set of revolutionary technologies, the question as to which of them should be space-flight validated must be addressed. The following criteria have been established and will be applied relative to each technology to assess its value for incorporation into NM]' validation nights:

A. Impact on 21st century science missions
B. Revolutionary nature of breakthrough
C. Risk reduction by flight validation

Within these categories, the technologies will be evaluated on a scoring system from 0-3, as indicated in Table 1:

TABLE 1. TECHNOLOGY VALUE CRITERIA

| | |
|---|---|
| **A. Impact on 21st century science missions** | (Value 0-3) |
| 3 Critical for many missions | |
| 2 Critical for some mission types and/or valuable for many | |
| 1 Valuable for some mission types | |
| 0 No significant impact on future missions | |
| **B. Revolutionary nature of breakthrough** | (Value 0-3) |
| 3 A completely new approach with orders of magnitude improvement in factors relevant to mission life cycle costs | |
| 2 An improvement offering a 10 fold improvement in relevant factors | |
| 1 An improvement offering less than a 10 fold enhancement in relevant factors | |
| 0 An incremental improvement | |
| **C. Risk reduction by flight validation** | (Value 0-3) |
| 3 Flight validation is both necessary and sufficient to ensure the incorporation of this technology into future science missions | |
| 2 Flight validation will significantly reduce the perceived risk of incorporation compared to ground validation alone | |
| 1 Flight validation will reduce the perceived risk of incorporation compared to ground validation alone | |
| 0 Flight validation offers no advantages over ground validation, or ground validation is sufficient to ensure future incorporation into science missions | |

The Technology Value is obtained by multiplying the individual scores from the three categories:

**Technology Value = A x B x C**

This is equivalent to a logical requirement that all three conditions are necessary, i.e.. it is the overlap of the three attributes that determines the priority for validation on an NMP flight, as shown schematically in Figure 6.

PROGRAM FOCUS

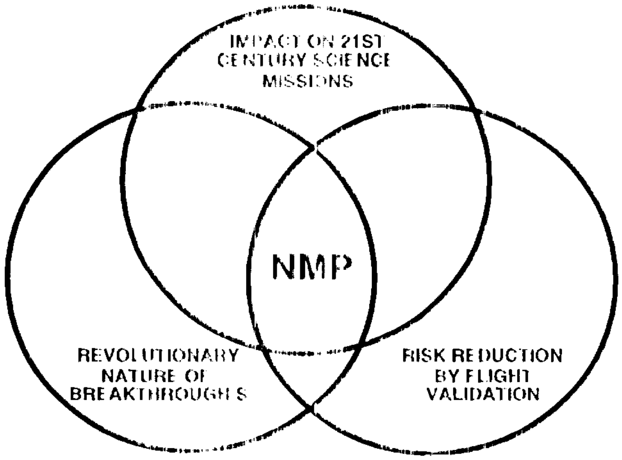


FIGURE 6

Preliminary Technology Values will be assigned by the IPDTs to the technologies they propose for flight. A final score will be assigned by the Program Manager based on the IPDT input, and normalized across teams. Technologies proposed by sources outside the IPDT's will be evaluated and assigned a Technology Value directly by the Program Manager. The NMP Science Working Group (SWG) membership, including other members of the science community brought in to augment the expertise for the associated flight, will also be asked to provide Technology Value scores for all the technologies under consideration. In any case where the SWG assessment is consistently at variance with the IPDT normalized scores, the Program Manager will work with the IPDT and SWG members to resolve the discrepancy and arrive at a final score.

2. Readiness Probability

The technologies will also be evaluated as to their probability of readiness for a given flight, and thus what the probability is that, if selected, they will be delivered on schedule and within budget for integration into the relevant validation flight. The Readiness Probability is based on an assessment of the technology's maturity--that is how close it is to its final stage of development----and thus its likelihood of delivery on time and within budget.

Preliminary Readiness Probability will be assigned by the IPDTs. In some cases, a Flight Team will already have been identified for a mission, and they will have the prerogative to further investigate the basis for these values. After consulting with the IPDT co-leads, they will finalize the scores based on this more detailed evaluation. The Readiness Probability for technologies proposed by sources outside the IPDTs will be assigned by the respective Flight Team. If the Flight Leads have been identified at this point, the Readiness Probability will be reassessed once they are brought on board.

3. Determination of Expected Value

Since individual NMP validation flights must define and meet concrete integration and test schedules, the effective value of a technology associated with a given flight depends not only on its "raw" Technology Value, defined above, but also on the probability that it will be delivered in time for flight. An adjusted value score, the Expected Value, is obtained by multiplying the Technology Value by the Readiness Probability:

**Expected Value = Technology Value x Readiness Probability**

Those technologies with the highest Expected Value are the most likely candidates for flight execution on NMP validation flights. Table II summarizes the responsibilities for generating preliminary and final scores of individual technologies proposed for flight validation.

TABLE II. RESPONSIBILITY FOR ASSIGNING TECHNOLOGY SCORES

| | GENERATE | APPROVE |
|---|---|---|
| Technology Value | IPDT/SWG | Program Manager |
| Readiness Probability | IPDT | Flight Lead |

## 4. Final Selection Process

After evaluating the Expected Value of each of the technologies proposed by the IPDT, the ADT will use these data to generate several refined candidate advanced technology payload flights focused on validating the highest priority technologies. The Program Manager will determine the optimum mix of technologies for any given validation flight or set of flights.

This final determination will be based on evaluating sets of technologies matched with appropriate potential validation flights, with consideration given to:

i) the combined Expected Value of the technologies and their compatibility for integration into candidate validation platforms.

ii) funding availability *vs.* overall mission costs including those associated with the development, integration, on-board operation, and validation requirements of the technologies

iii) overall programmatic guidelines and constraints in spacecraft mass, size, power and flight schedule

iv) other programmatic considerations, such as the net scientific value of the flights, the cost-effectiveness of the validation plans, the schedule of planned science missions requiring or benefiting from the technologies, and the ensuing benefits to the US industrial infrastructure and commercial space enterprise.

The final outcome is a recommendation to NASA HQ of a set of validation flights with their associated technology complements. After acceptance by NASA HQ, Flight Teams will be formed and Flight Leads identified. They will provide a more detailed assessment of the integration and validation of the impact, cost, and other constraints of the selected technologies. If any incompatibilities emerge, they will be brought forward to the Program Manager for resolution. The decision processes in the technology selection phase are shown schematically in Figure 7.

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## PHASE II: SELECTION OF TECHNOLOGIES FOR FLIGHT DEVELOPMENT

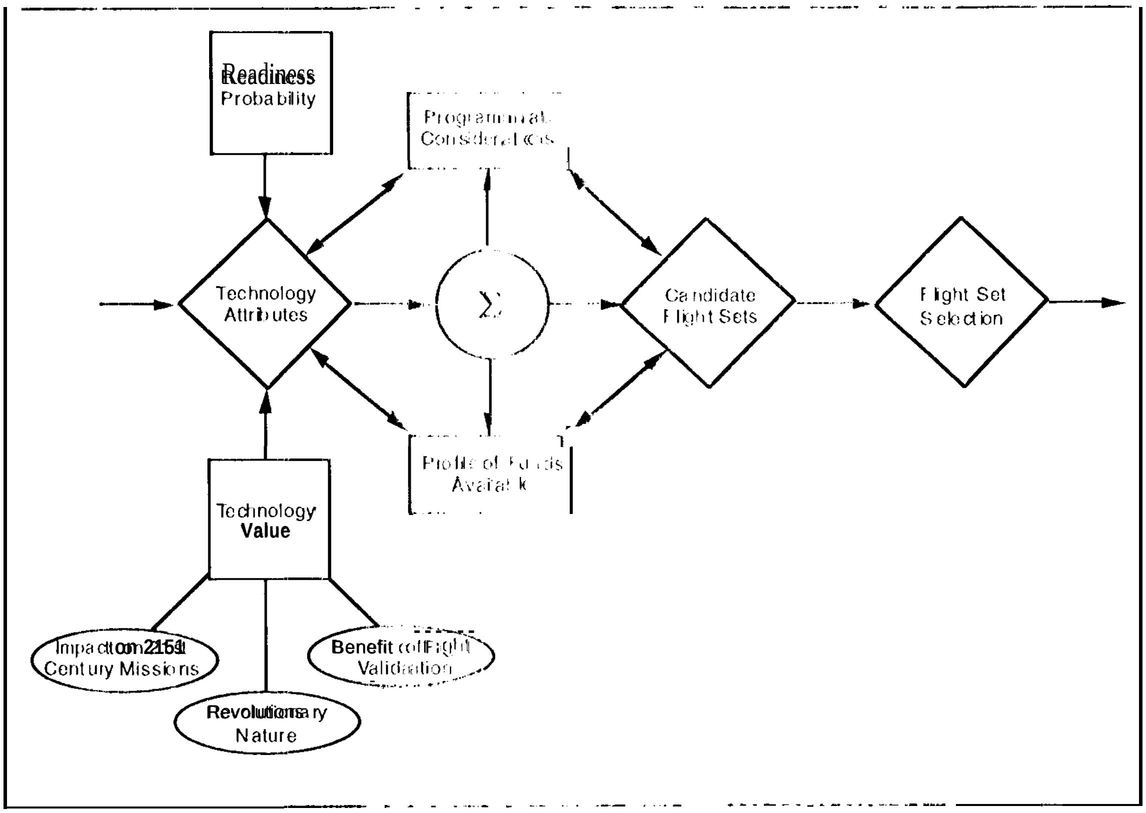


FIGURE 7

**Technology Flight Acceptance**

Once a breakthrough technology has been approved by NASA HQ for validation on an NMP flight, there still remain two tasks to ensure its successful delivery on schedule and within budget to the Flight Team.

- Technology Classification
- Passing Readiness Gates.

### *Technology Classification*

The impact on a validation flight of failure of a technology to achieve readiness on schedule for flight depends on the nature of the technology and its assigned role in the flight. To assess this impact and designate the manner in which the development process must be managed, we classify the technologies into three categories.

Category 1: . . ...Essential.

Technologies in this category are essential to the mission--the proposed flight cannot be carried out as designed without this technology. An example is solar electric propulsion (SEP) for the first deep space flight. Without SEP, flyby of the selected comet and asteroids cannot be achieved on the designated launch vehicle. Thus, failure to achieve readiness in time for flight would require a redesign of the mission itself. in general, only a few technologies will be selected in this category.

Category II: Fundamental

These technologies are fundamental in that the mission cannot be carried out as defined without this functional capability, but existing technologies could be substituted if the breakthrough technology did not pass all three gates. Since the aim of the NMP flights is to provide testbeds to demonstrate new capabilities in their full operational mode, the majority of technologies selected are expected to fall into this category.

Category III: Enhancing

Technologies in this category simply enhance the overall technology value of the mission, and are considered experiments. The functional capabilities they provide are not required for the completion of the mission as designed, and therefore if they do not pass the three gates, the mission can simply be flown without them. Typically, these technologies represent key enabling features of future capabilities flown as precursors of the full system capability.

Technologies selected for flight will be categorized by the Flight Team.

## *Passing Readiness Gates*

Program Management has defined three readiness checkpoints, or gates through which the technologies must pass on their way to flight acceptance. The three gates are defined and described below:

1. Technology Readiness Review
2. Key Technology Hardware/Software Demonstration
3. System Hardware/Software Demonstration

1. Technology Readiness Review

The first gate will consist of a written review of the respective technology's readiness state by a peer review group, selected by the Flight Team Leads, who will be experts in the field of that particular technology. The review will cover the status of the technology's development to date, and the cost needed to deliver it on schedule for infusion into the validation flight. It will also cover the proposed in-flight validation approach. The Technology Readiness Review will be conducted before or during the Interim Design Concurrence Review. If the technology successfully passes this gate, that is, if the review indicates a viable plan to develop and deliver the technology within budget and on time, it will move on to the next gate.

2. Key Technology Hardware/Software Demonstration

The second gate will consist of a demonstration of the key features of the technology's hardware and/or software, to determine whether they meet planned specifications, and whether development is on schedule. This demonstration will be conducted before or during the Detailed Design Concurrence Review is held. A review group, consisting of experts in the relevant technology and flight team experts, will be designated by the Flight Team Lead.

3. System Hardware/Software Demonstration

The third and final gate consists of a system-level demonstration of the technology's hardware and software. At this gate, the technology will be tested yet again, to determine that the overall system functions as specified, and whether the technology will meet its delivery deadline. Maintaining as much continuity as possible, the Flight Team Lead will identify a review group to carry out this final review. The third gate will be conducted before the start of Assembly Test and Launch Operations.

The technology provider and the Flight Team negotiate the content and schedule for the three gates. A simple form will be signed by both to document the negotiated agreement. A risk balance will naturally be achieved in these negotiations since the Flight Team desires a solid complement of technologies to make a worthwhile and exciting flight, and the technology providers desire the Flight Team to successfully demonstrate their technologies. The 11'1)'1's will facilitate the development and delivery of the technologies, and in that capacity will provide advanced and timely advice in a proactive manner to the Flight Team. Continued funding of the technology through to delivery to the Flight Team is contingent on successfully passing each of the three gates. The decision processes in the delivery of technologies for flight acceptance phase are shown schematically in Figure 8. A summary of the entire Technology Selection Process is shown in Figure 9.

It should be noted that the decision making processes in the identification of high-priority candidate technologies phase and the technology selection phase are not strictly sequential and linear as indicated in this model. For example, at the start of the first phase, the 1}'1)1' areas were identified based on an initial assessment of the technology pipeline. By the end of the phase, the range of high-priority technologies identified by the technology experts in the IPDTs, or brought to the Program's attention by other sources, may call for a reexamination of the team areas and scopes. Similarly the approach to technology and flight set selection in the second phase is inherently a concurrent process, calling for an initial evaluation and subsequent cycles of refinement leading to a final decision. These feedback loops are omitted from the figures and text for simplicity.

PHASE 111. DELIVERY OF TECHNOLOGIES FOR FLIGHT

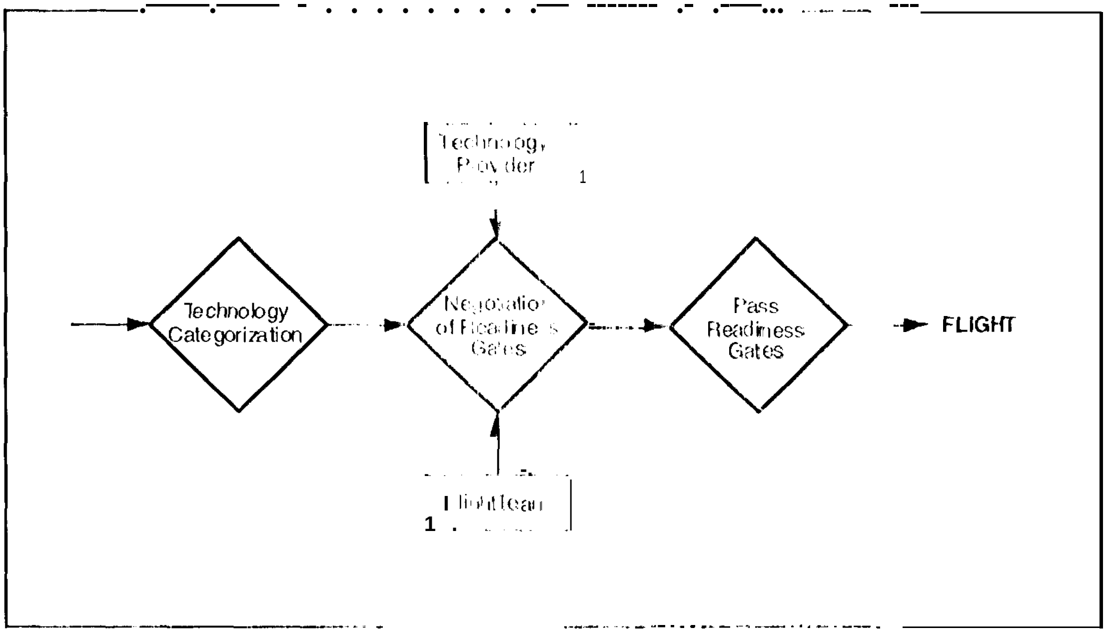


FIGURE 8

## SUMMARY OF TECHNOLOGY AND FLIGHT SELECTION PROCESS

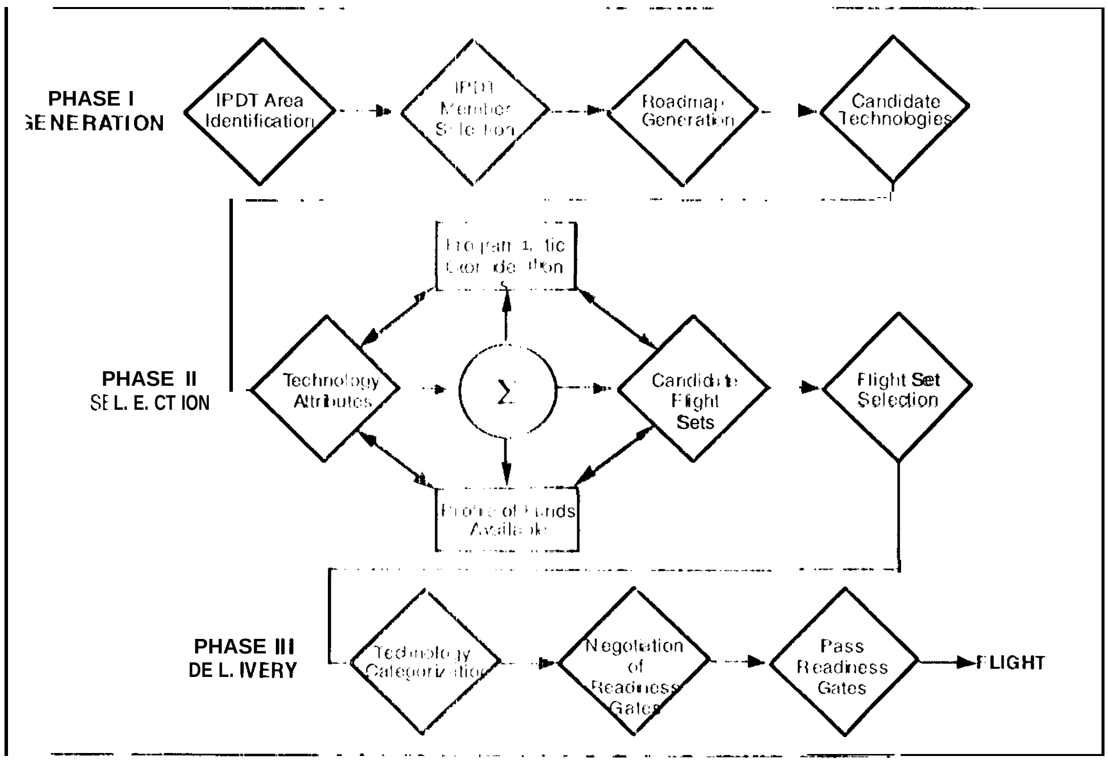


FIGURE 9

## CONCLUSION

The New Millennium Program is developing and flight-validating **revolutionary** technologies to enable a new era in space flight, one where there **will** be frequent launches of **low-cost, highly** capable spacecraft. Starting in 1998, it will launch three deep space and three earth orbiting missions that will test technologies being developed by its Integrated Product Development Teams. The technologies eventually accepted and delivered for flight validation will be chosen after being subjected to a three-phase selection process to ensure that **they** will provide the **specific capabilities** required for the science missions of the next century.

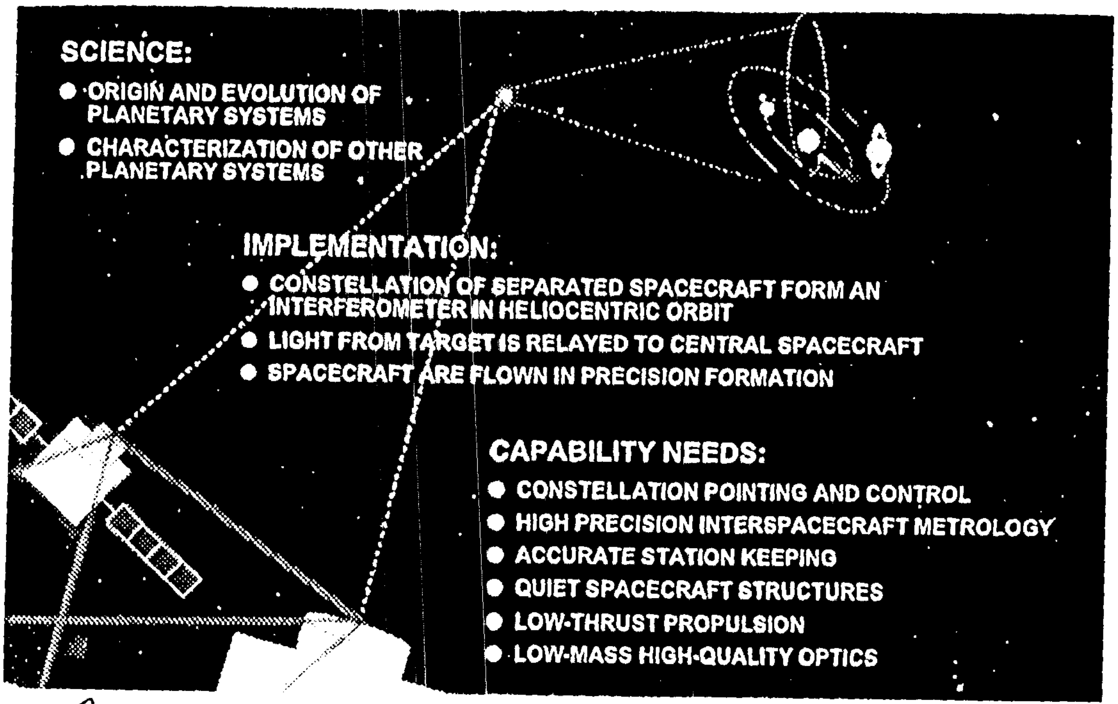


*Figure 2. Extrasolar Planetary Imaging*

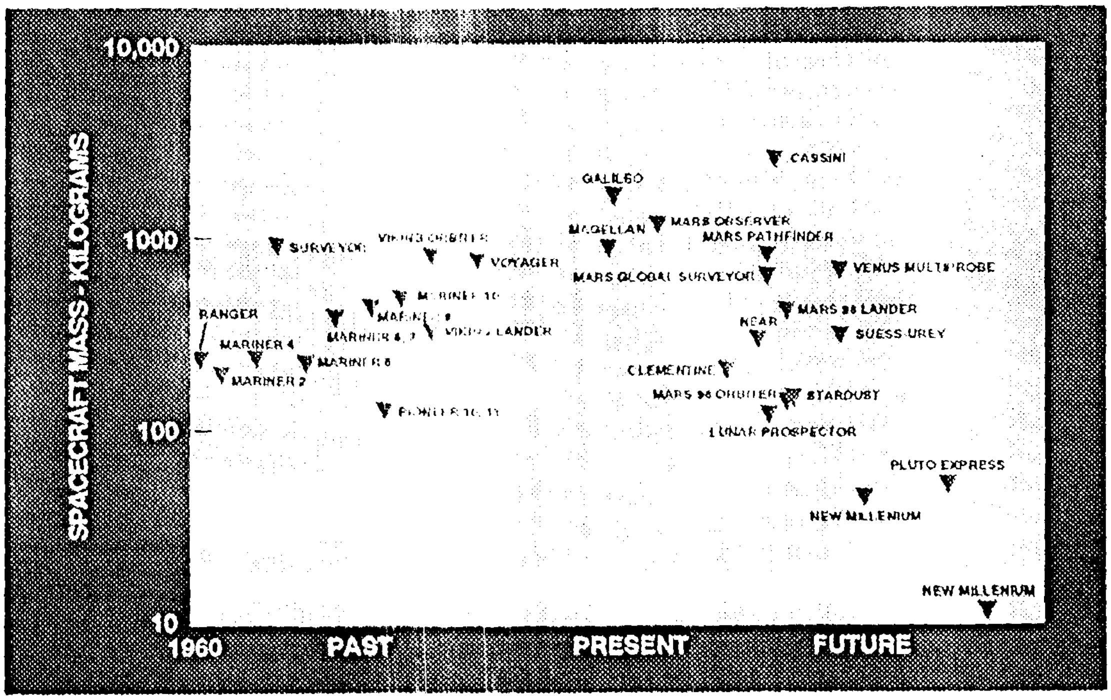


*Figure 3. Spacecraft Dry Mass vs. Time*

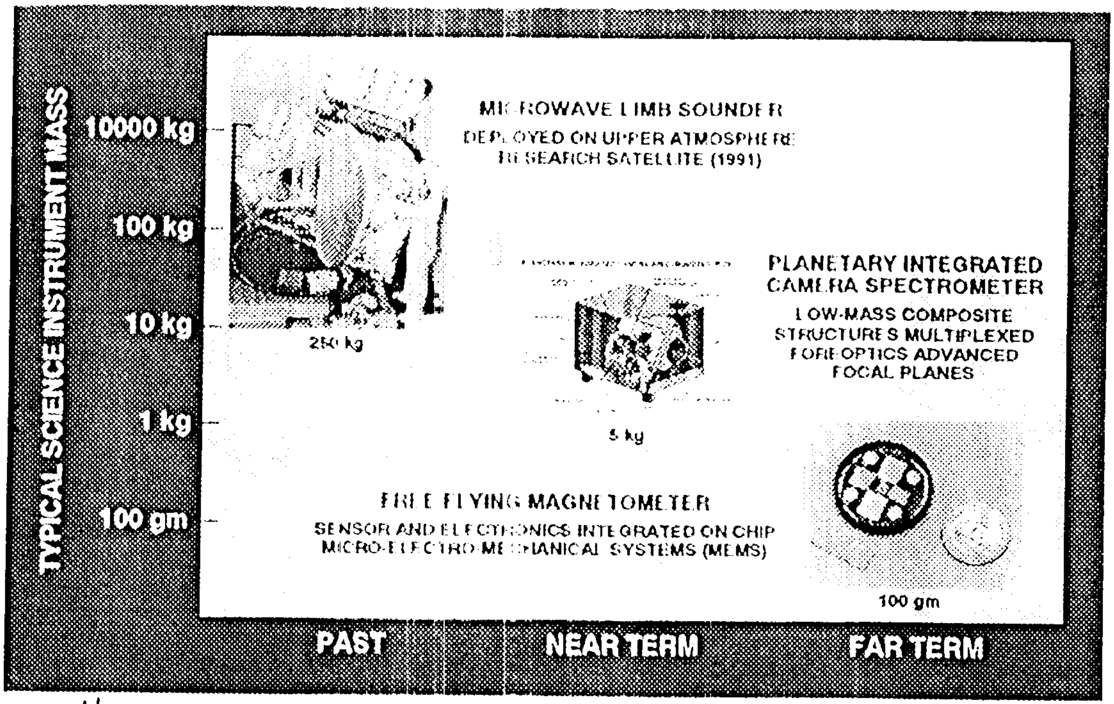


Figure 4. Powerful Microinstruments - Instrument Miniaturization

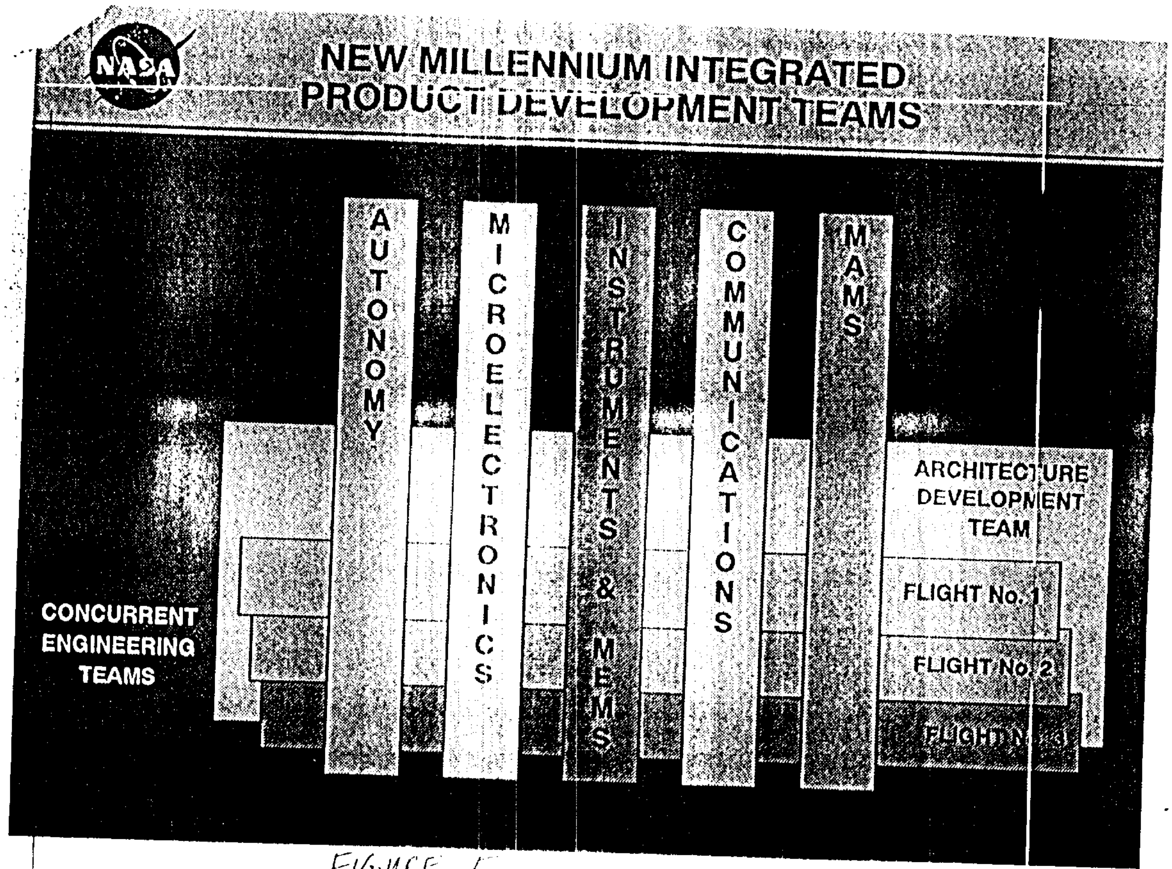


FIGURE 5